

Study of Blockage Effects on Scouring Pattern Downstream of Box Culverts

By

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A thesis submitted in fulfilment
of the requirement for the degree of
Doctor of Philosophy



University of Technology Sydney
School of Civil and Environmental Engineering

November 2015

To

BIHE teachers

who sacrifice their lives to spread the knowledge

and to

Pouyan

for his ceaseless support and love.

Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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November 2015

Abstract

Culverts are locations in water courses where a constriction in the water occurs and therefore where blockage of some type is likely to occur. Blockage of culverts commonly occurs during flood events. When a culvert is partially blocked at the inlet, the flow structure in the barrel and at the outlet will change and consequently may result in the failure of the culvert. Despite this, the impacts of blockage on culvert hydraulics and downstream waterways have not received consideration in the literature. The purpose of this study is to mitigate this deficiency by reporting on an investigation into scouring at the outlet of partially blocked culverts.

The aims of this study can be categorised as:

- to investigate the effects of blockage on scour geometry and to develop predictive equations;
- to study the flow structure at the outlet of partially blocked culverts and compare it with a non-blocked culvert to explain the previous findings;
- to conduct the experiments in unsteady flow conditions which are more similar to flood events to validate the general findings

To achieve these aims experimental tests were conducted under steady flow to investigate a relationship between the maximum scour extents, blockage ratio of the culvert and the flow characteristics. Both non-blocked and partially blocked conditions were considered. Consideration of the results obtained showed that the scoured area and maximum scour depth increased with partially blocked culverts conditions compared with equivalent non-blocked culverts. Because complete protection against scour is too expensive, generally, the maximum scour depth of the

scour hole has to be predicted to minimize the risk of failure. Therefore, empirical equations were developed to predict the maximum scour depth, length and width at the outlet of blocked culverts.

In the next stage and to have a better understanding of the turbulent flow conditions at the outlet of a partially blocked culvert an experimental program was designed to measure the longitudinal, lateral and vertical velocity components through the culvert barrel centreline and at the outlet. Tests were conducted in both non-blocked and partially blocked condition. Based on that, the turbulent flow characteristics such as turbulence intensity, turbulent kinetic energy and Reynolds shear stress were obtained for each condition. Results showed that the turbulent flow characteristics in the partially blocked condition are significantly different in the barrel and at the outlet compared to a non-blocked condition of the same discharge.

As the final step of this study, a test program was conducted under unsteady conditions in partially blocked and non-blocked culverts. The results were compared with previous results of steady tests and showed an agreement with previous steady flow tests.

Acknowledgments

Studying a PhD is a challenging and rewarding journey. I would like to express my sincere gratitude to a number of people who have made the completion of this journey possible. First of all, I would like to express my deepest gratitude to my supervisors, Associate Professor James Edward Ball, Professor Alireza Keshavarzi and Professor Bijan Samali for their guidance, suggestions, continuous support and encouragement throughout the challenging path of the research. I would like to acknowledge the care and support of Dr Hamid Valipour who was in the supervisory board at the early stages of this research.

I am greatly indebted to Baha'i Institute for Higher Education (BIHE) for providing the opportunity of the graduate study for Baha'i youth in Iran without which I could never be here. I wish to express my sincere gratitude especially to Mr. Mahmoud Badavam and Professor Bijan Samali for initiation of this research opportunity.

I am very thankful to the friends and technical staff of the Hydraulics Lab of UTS, especially the lab manager Mr Rami Haddad.

I am always grateful to my parents; my dearest mother, Mahin, my beloved father, Aman and to my sisters Samin and Samareh. Their unconditional love and support has led me through the challenges of life.

Finally and above all, I cannot begin to express my unfailing gratitude and love to my husband, Pouyan, for being the boundless source of love and encouragement. Who supported me since I intended to start this journey and travelled thousands of miles away from home country with me to make my dream come true.

List of Publications Related to This Thesis

Journal Articles

1. SOROURIAN, S., KESHAVARZI, A., BALL, J. & SAMALI, B. 2013. Study of Blockage Effect on Scouring Pattern Downstream of a Box Culvert under Unsteady Flow. *Australian Journal of Water Resources*. Engineers Australia, Vol.18, Issue 2,180-190.
2. SOROURIAN, S., KESHAVARZI, A., BALL, J. 2015. Scour at partially blocked box-culverts under steady flow. *Proceedings of Institution of Civil Engineers- Water Management*, Thomas Telford Ltd, Published online 28 October 2015.

Conference Papers

1. SOROURIAN, S., KESHAVARZI, A., BALL, J. 2015. Turbulent Flow Characteristics at the Outlet of a Partially Blocked Box Culvert. Proceedings of 36th International Association for Hydro-environment Research World Congress, 28 June-3 July 2015, Delft, Netherlands.
2. SOROURIAN, S., KESHAVARZI, A., BALL, J. & SAMALI, B. 2014. Location of the maximum scouring depth at the outlet of partially-blocked and non-blocked box culvert. Proceedings of 7th International Conference on Fluvial Hydraulics, River Flow 2014. CRC Press, 1475-1480.
3. SOROURIAN, S., KESHAVARZI, A., BALL, J. & SAMALI, B. 2014. Prediction of Scouring Depth at the Outlet of Partially Blocked Box Culvert.

In: World Environmental and Water Resources Congress 1-5 June 2014
Portland, Oregon. American Society of Civil Engineers, 1352-1361.

4. SOROURIAN, S., KESHAVARZI, A., BALL, J. & SAMALI, B. 2013.
Study of Blockage Effect on Scouring Pattern Downstream of a Box Culvert
under Unsteady Flow. 35th International Association for Hydro-environment
Research World Congress World Congress. Chengdu, China.
5. SOROURIAN, S., KESHAVARZI, A., SAMALI, B. & BALL, J. 2012.
Study of blockage effect on scouring pattern downstream of a box culvert. In:
SAMALI, B., ATTARD, M. M. & SONG, C., eds. Proceedings of the 22nd
Australian Conference on the Mechanics of Structures and Materials, 2012
Sydney. CRC Press, Balkema, 741-744.

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List of Notations

A	cross section area of the culvert outlet
A_B	blockage area at culvert inlet
A_F	flow area at culvert inlet
A_s	scoured area
B	blockage ratio
C_c	sediment coefficient of curvature
C_h	coefficient for culvert drop
C_s	coefficient for culvert slop
C_u	sediment coefficient of uniformity
D	circular culvert diameter
DI	discharge intensity
d_0	outlet diameter in circular-shape culverts
d_m	effective grain size
d_s	scour depth
d_{sm}	maximum scour depth
$d_{sm(t=i)}$	maximum scour depth at time i ($i = 10, 20, \dots, 110$) of the test
$d_{s0(t=i)}$	Scour depth at culvert outlet at time i ($i = 10, 20, \dots, 110$) of the test

d_{50}	median grain size of bed material
g	gravity acceleration
F_d	densimetric Froude number
F_{d95}	modified densimetric Froude number
F_r	flow Froude number
F_{rp}	prototype Froude number
F_{rm}	model Froude number
H	culvert height
H_v	velocity head
H_w	headwater depth
h_B	height of blockage plate
h_d	depth of water at culvert outlet
h_e	entrance loss
h_f	friction loss
h_t	tail water depth
h_u	upstream depth of water
KE_x	kinetic energy in x direction
KE_y	kinetic energy in y direction

KE_z	kinetic energy in z direction
L	culvert length
L_t	total scour length
Q	flow rate
R^2	coefficient of correlation
R_H	Hydraulic radius
RSS	Reynolds shear stress
S_0	bed slope
S	culvert slope
S_E	standard error of estimate
S_f	energy gradient
TI_x	turbulence intensity in x direction
TI_y	turbulence intensity in y direction
TI_z	turbulence intensity in z direction
t	time of experiment
u	mean flow velocity
u_m	flow velocity in the model
u_p	flow velocity in prototype

u^*	shear velocity
u_c^*	shear velocity at initiation of motion
v_x	flow velocity in x direction
v_y	flow velocity in y direction
v_z	flow velocity in z direction
v_x'	turbulent fluctuations of the flow velocity in y direction
v_y'	turbulent fluctuations of the flow velocity in x direction
v_z'	turbulent fluctuations of the flow velocity in z direction
W	culvert width
W_c	half width of culvert
W_{sm}	maximum scour width
X	horizontal axis (flow direction)
X_m	length characteristic in model
X_p	length characteristic in prototype
x_s	horizontal distance from the outlet
x_{sm}	location of maximum scour depth along horizontal axis
$x_{sm(t=i)}$	location of maximum scour ole in horizontal axis at time i of the test
y_s	width of scour hole at any location along y axis

z	depth of water from culvert invert
λ	scaling ratio
ρ	water density
ρ_s	sediment density
σ_g	sediment geometric standard deviation

List of Notation Used by Other Researchers

b	depth of tailwater (in Figure 2-5)
h^*_{100}	cube root of the volume of scour after 100 hours (in Figure2-5)
H_b	height of the drop (in Figure 2-5)
E_0	energy of the jet at the tail water surface (in Figure 2-5)
W_m	mean fall velocity (in Figure 2-5)
B	width of the flow (in Figure2-6)
V_m	mean velocity (in Figure2-6)
$\bar{\gamma}_{st}$	Buoyant specific weight of bed material (in Figure2-6)
H_0	inside height of culvert (in Figure2-7)
W_0	Inside width of culvert (in Figure2-7)